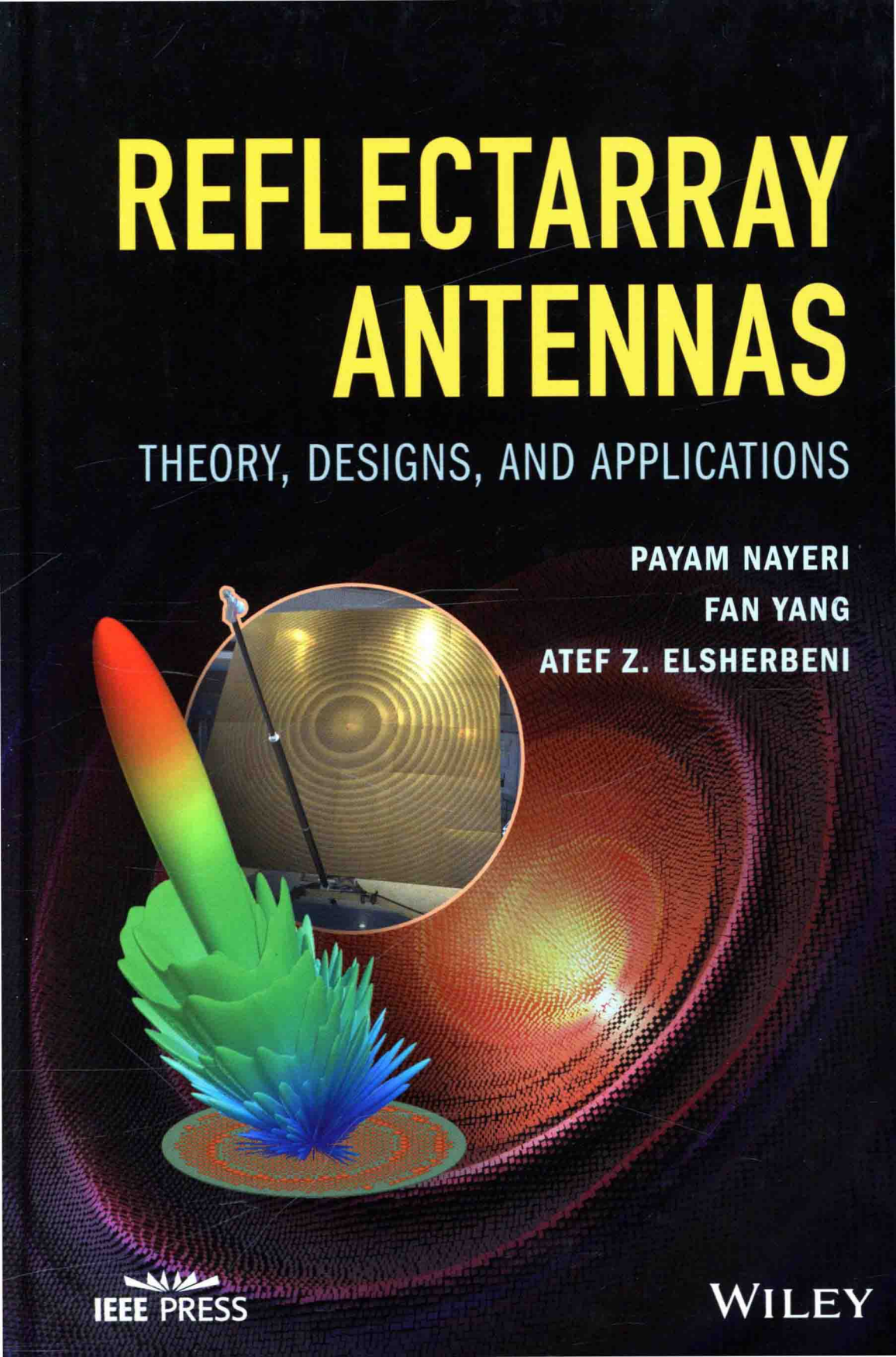
REFLECTARRAY ANTENNAS

THEORY, DESIGNS, AND APPLICATIONS

PAYAM NAYERI
FAN YANG
ATEF Z. ELSHERBENI



IEEE PRESS
WILEY

A comprehensive, practical review of reflectarray theory, design, and state-of-the-art implementations

This book provides engineers with a comprehensive review of the state-of-the-art in reflectarray antenna research and development. The authors describe, in detail, design procedures for a wide range of applications, including broadband, multi-band, multi-beam, contour-beam, beam-scanning, and conformal reflectarray antennas. They provide sufficient coverage of basic reflectarray theory to fully understand reflectarray antenna design and analysis such that the readers can pursue reflectarray research on their own. Throughout the book numerous illustrative design examples including numerical and experimental results are provided.

The reflectarray antenna is a hybrid design combining many of the best features of reflector antennas and printed arrays, in a low-profile, low-mass, highly cost-effective design. Although the concept of reflectarray antennas was first introduced in the early 1960's, it did not receive serious attention until the advent of printed circuit board technology in the 1990's made it practicable. Since then continuous research on reflectarray antennas has yielded several groundbreaking applications, including multi-beam antennas for point-to-point communication, beam-scanning antennas for radar applications, and spatial power combining reflectarray systems, among others.

Featuring in-depth theoretical analysis along with practical design examples, *Reflectarray Antennas* is an excellent text/reference for engineering graduate students, researchers, and engineers in the field of antennas. It belongs on the bookshelves of university libraries, research institutes, and industrial labs and research facilities.

Specifically, the book:

- Provides engineers and researchers in electromagnetics, microwaves, and antennas with a systematic overview of reflectarray antenna design and analysis techniques
- Includes several design examples of reflectarray antennas along with numerical and experimental results
- Offers detailed design procedures for a wide range of applications, including broadband, multi-band operation, multi-beam scanning, contour-beams, beam-scanning systems, conformal reflectarray antennas, transmitarrays, terahertz reflectarrays, and more
- Features detailed real-world implementation examples for each design covered

PAYAM NAYERI, PhD, received his doctorate in electrical engineering from the University of Mississippi and holds a degree in applied physics. He is an Assistant Professor in the Electrical Engineering Department at Colorado School of Mines, USA.

FAN YANG, PhD, earned his doctorate in electrical engineering from the University of California at Los Angeles (UCLA), in 2002. He is a Professor in the Electronic Engineering Department, Tsinghua University, China.

ATEF Z. ELSHERBENI, PhD, is a Distinguished Chair Professor and Electrical Engineering Department Head at Colorado School of Mines, USA. He holds a doctorate in Electrical Engineering from Manitoba University, Canada.

Cover Design: Wiley
Cover Images: (Background) © Andrey Prokhorov/Gettyimages;
(Foreground) Courtesy of Payam Nayeri, Fan Yang, and Atef Z. Elsherbeni

www.wiley.com

WILEY IEEE PRESS

Also available as an e-book

ISBN 978-1-118-84676-6

IEEE PRESS

NAYERI
YANG
ELSHERBENI

REFLECTARRAY ANTENNAS

WILEY

Reflectarray Antennas: Theory, Designs, and Applications

Payam Nayeri
Colorado School of Mines
USA

Fan Yang
Tsinghua University
China

Atef Z. Elsherbeni
Colorado School of Mines
USA

WILEY

IEEE PRESS

This edition first published 2018

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication data applied for

ISBN: 978-1-118-84676-6

Cover design by Wiley
Cover images: (Background) © Andrey Prokhorov/Gettyimages;
(Foreground) Courtesy of Payam Nayeri, Fan Yang, and Atef Z. Elsherbeni

Set in 10/12pt Warnock by SPi Global, Pondicherry, India
Printed in Singapore by C.O.S. Printers Pte Ltd

10 9 8 7 6 5 4 3 2 1

Reflectarray Antennas: Theory, Designs, and Applications

To my parents who I am eternally grateful for their love, support, and encouragement throughout my career

Payam Nayeri

To my colleagues and students, and to my family

Fan Yang

To my wife, Magda, daughters, Dalia and Donia, son, Tamer, and the memory of my parents

Atef Z. Elsherbeni

Foreword

Although the concept of the reflectarray antenna was first introduced in 1963, the vast interest in it did not come about until in the late 1980s with the development of low-profile microstrip antennas. From the word *reflectarray*, it can be deduced that this is an antenna that combines the unique features of a parabolic *reflector* and a phased *array*. Thus, a low-profile reflectarray consists of an array of microstrip elements that are provided with a set of pre-adjusted phases to form a focused beam when illuminated by a feed, in a similar way to a parabolic reflector. The array elements can be printed onto either a flat surface or a slightly curved surface and have been demonstrated to have the ability to produce a high-gain pencil beam, a contour-shaped beam, multiple beams, or an electronically scanned beam. Because the array elements in a reflectarray are not physically interconnected, it can produce a high-gain beam with relatively high efficiency similar to that produced by a parabolic reflector. There were several pioneers that initiated the study of printed reflectarrays during the late 1980s. I thought about the idea of a reflectarray due to my earlier work experiences with microstrip antennas and frequency selective surfaces (FSS). At certain resonant frequencies, the FSS can only reflect as a nearly perfect conductor since all elements are identical. It cannot cause the reflected waves to form a phase-coherent beam. However, if each FSS element is designed differently with appropriate phase delay, a coherent beam can then be formed and a printed reflectarray is consequently formed.

This book gives a comprehensive presentation of reflectarray antennas. Chapter 1 is a general overview of the operating principles as well as the developmental history of reflectarray antennas. Chapters 2 through 5 provide very complete and detailed design and analysis techniques, including the important element characterization and selection, radiation efficiency analysis and system design, various radiation analysis approaches and tradeoffs, and the most critical bandwidth issues and analysis. Chapter 6 gives a few specific design examples; in particular, a Ku-band step-by-step design example and a circularly polarized reflectarray design. It is well known that the bandwidth limitation generally presents critical issues in reflectarray design. Chapter 7 is devoted to broadband solutions by presenting several bandwidth widening techniques and multiband approaches. The Terahertz, infrared, and optical frequencies have been found to be the frontier of research and application for antennas. Reflectarray antennas have also found applications in these extremely high frequency areas and are presented in Chapter 8, where the critical issues of material characterization and element loss are discussed. Low-loss dielectric resonators, used as elements, are also presented in this chapter. A single reflectarray antenna can not only be designed to produce a high-gain

pencil beam, but, due to its many array elements, also has the ability to generate a specifically contour-shaped beam as well as multiple beams. Chapter 9 gives a thorough presentation of the design approaches, which include direct design approaches and synthesis design approaches for a single reflectarray to radiate a contour-shaped beam or multiple beams. Chapter 10 engages in discussion about a reflectarray's beam scanning capability and design approaches. One of the key advantages of the reflectarray is its ability to achieve fast electronic beam scanning by implanting a low-loss phase shifter into each of its elements without the need for expensive transmit/receive modules and high-loss power division network. Thus, the reflectarray, owing to the hybrid nature of reflector and array, can behave like an efficient high-gain parabolic reflector and a relatively low-cost phased array. Finally, Chapter 11 discusses several emerging and future applications of reflectarray antennas, such as a reflectarray conformally mounted on curved surfaces, satellite applications, integration with solar cells, amplifying reflectarrays, dual-reflectarrays, very large aperture applications, and so on.

By comparing this book with the very first reflectarray book published by the Wiley-IEEE Press (Huang and Encinar) in 2008, this book not only gives more updated information, but also gives more detailed analysis and design presentations. The authors of that 2008 book also presented their own pioneering contribution in the areas such as broadband design using sub-wavelength patch elements, a special phase synthesis approach, and single as well as multilayer approaches. In particular, a single layer design with tri-band circular polarization performance was achieved. It was a cooperative effort that fulfilled my contractual request from the Jet Propulsion Laboratory while the authors were teaching at the University of Mississippi. A unique split-square ring element was also used to achieve excellent circular polarization for this single-layer multiband reflectarray. In that book, the authors presented their own contributions in the area of Terahertz and infrared reflectarray applications. In addition, the synthesis technique for a single reflectarray to achieve multiple beams and specifically shaped beams was presented as well. The electronic beam scanning capability of the reflectarray was also fully discussed with several well-presented new design approaches.

This book is well organized and has significant amount of information in design and analysis with many practical application results augmented with adequate number of references to help the readers to comprehend. Undoubtedly, I believe this book is not only well suited as a university text book but also is an excellent source of design and analysis information for antenna engineers for many years to come.

Dr. John Huang
Principle Engineer, retiree of
The Spacecraft antenna research group
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, USA

Preface

High-gain antennas are an essential part of long-distance wireless communications, radar, and remote sensing systems, which vary with frequency, coverage, resolution, and flexibility of operation. The conventional choices for antennas in these systems were typically reflectors, lenses, or arrays. In recent years, however, a new generation of high-gain antennas has emerged that combines the favorable features of both printed arrays and reflector antennas and creates a high-gain antenna with low-profile, low-mass, and low-cost features. This antenna is known as the reflectarray.

The reflectarray is an antenna with a flat reflecting surface consisting of hundreds of elements and an illuminating feed antenna. The hybrid nature of the reflectarray antenna offers more flexibility in aperture phase control and can provide advantages over both reflectors and array antennas for many applications. The elements of the reflectarray are individually designed to reflect the electromagnetic wave with a certain phase to compensate for the phase delay caused by the spatial feed. The phase shift of the elements is realized using various methods such as variable-size elements. Single and multilayer reflectarrays have been designed to achieve broadband and multiband performance from microwave frequencies up to the THz range. Meanwhile, the direct control of the phase of every element in the array allows multi-beam or shaped beam performance with single or multiple feeds. Another advantage of reflectarrays is the ability of the antenna to scan the main beam to large angles off broadside. The advantages of reflectarrays, such as being low-profile, lightweight, and having conformal geometry, make it desirable for various communication systems, especially for mobile platforms. Its applications in space exploration, satellite communications, remote sensing, and radar systems are rising, and will continue to increase in the future. In addition, the current printed circuit board (PCB) fabrication technology and available low-cost commercial laminates, allows for low-cost rapid prototype fabrication. This is also leading to commercial implementation and large-scale fabrication of reflectarray antennas. The potential of reflectarray capabilities has not yet been fully exploited. Researchers in this field are constantly presenting new ideas and designs ranging from advanced materials to multifunctional system designs. As such, it is expected that this field will remain an active area of research, and there is no doubt that reflectarrays will become an important member of the antenna family.

The aim of the book is to provide scientists and engineers in the fields of antenna, microwave, and electromagnetics, with up-to-date knowledge of reflectarray antenna theories, designs, and applications. This book will provide the reader with an overview of the reflectarray antenna research history and state-of-the-art, good knowledge of the

basic theories for design and analysis of reflectarray antennas, and detailed design procedures for a wide range of diversified and advanced applications.

The prerequisite for this book is that the readers should be familiar with the basics of antenna engineering. The first part of this book includes the fundamental theories of reflectarrays, and is intended for engineers that know the basics of antenna theory and are becoming familiar with this new generation of high-gain antennas. Chapter 1 introduces the reflectarray concept and historical backgrounds, and provides an overview of this book. Chapter 2 provides a comprehensive coverage of aperture phase requirements in reflectarray systems, phasing element design methodologies, and element analysis techniques. Reflectarray system design and efficiency analysis are introduced in Chapter 3. A detailed coverage of the various methods to compute the radiation characteristics of reflectarray antennas is presented in Chapter 4. The bandwidth characteristics of reflectarray antennas are studied in detail in Chapter 5. A variety of reflectarray designs are presented in Chapter 6 that can serve as a useful reference for interested readers.

The second part of the book is intended for researchers and specialists that have a good knowledge of the basic theories in reflectarrays, and aim to design reflectarray antennas for specific applications/operations. It starts with a comprehensive overview of broadband and multiband reflectarray antennas in Chapter 7. Reflectarrays operating above microwave frequencies such as in the terahertz, infrared, and optical spectrums are introduced in Chapter 8. A detailed coverage of multi-beam and shaped-beam reflectarrays is presented in Chapter 9. Chapter 10 presents beam-scanning reflectarray antennas, where the extensive research on these types of reflectarrays is summarized and analyzed in a comprehensive fashion. The final chapter of this book, Chapter 11, is devoted to advanced reflectarray antenna configurations.

Acknowledgments

The work presented in this book was supported in part by the following institutions:

National Aeronautics and Space Administration (NASA)
National Science Foundation (NSF)
Tsinghua National Laboratory for Information Science and Technology
Chinese High-Technology Research and Development Program (863-Program)

The authors would like to thank the technical reviewers for their insightful feedback which enhanced the clarity and efficacy of this work. We would also like to express our sincere gratitude to our colleagues and students over these years: Dr. John Huang, Prof. Yahya Rahmat-Samii, Prof. Jianhua Lu, Prof. Shenheng Xu, Prof. Glenn Boreman, Prof. Hao Xin, Prof. Maokun Li, Dr. Ang Yu, Dr. Chye Hwa Loo, Dr. Wenxing An, Dr. Yilin Mao, Dr. Ahmed Hassan Abdelrahman, Dr. Huanhuan Yang, Dr. Ruyuan Deng, Mr. Yanghyo Kim, Ms. Bhavani Devireddy, Mr. Tamer Elsherbeni, Ms. Fang Guo, Mr. Xiaolin Zhu, Mr. Xiao Liu, Mr. Jun Luo, Mr. Xiangfei Xu, Mr. Lin Gao, Ms. Xue Yang, Mr. Martye Hickman, Mr. Junling Zhao, and Mr. Lin Xiong. We also greatly appreciate the generous contributions of ANSYS Inc. in providing us with HFSS and Designer simulation software, and Rogers Corp. for providing us with high quality laminates that have been used for many of the designs that are presented in this book.

Contents